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Farm ponds in southern China: Challenges and solutions for conserving a neglected wetland ecosystem

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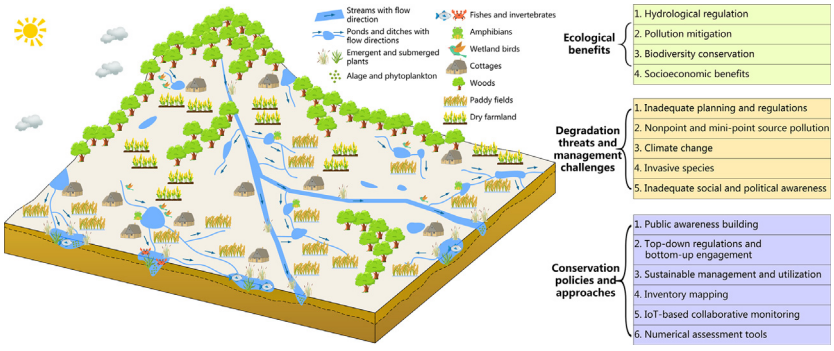
HIGHLIGHTS

- Farm ponds are small, scattered wetlands with a long history in southern China.
- They provided hydrologic, biogeochemical, biodiversity and socioeconomic functions.
- Their ever-increasing degradation threats and management challenges are evaluated.
- Policies and approaches are presented to form a collaborative conservation framework.
- It is a first synthetic analysis of ponds' ecological roles in developing countries.

GRAPHICAL ABSTRACT



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ABSTRACT

Farm ponds, which are sometimes numerous and widely distributed in agricultural regions, have faced widespread degradation in recent decades. Although conservation strategies for these biodiversity hotspots have gradually increased, appropriate approaches for developing country contexts are lacking. Farm ponds provided hydrologic, biogeochemical, and socioeconomic benefits to southern China for thousands of years, but they are facing contemporary threats and management challenges, including (1) inadequate planning in terms of construction and conservation regulations; (2) rural nonpoint source and mini-point source pollution; (3) climate change induced abnormalities in the hydroperiod and disturbance to wildlife; (4) invasive species; and (5) inadequate social and political capacity to consider ecological conservation. Because farm ponds function as wetland complexes that are embedded within or integral to larger ecosystems, their conservation requires collaborative efforts over scales ranging from within-pond to regional. We highlight approaches that build public awareness and involve inventory maps as a basis. Policies that integrate top-down regulation and bottom-up engagement and emphasize sustainable management and utilization are recommended to ensure the effectiveness and continuous improvement of conservation programs. Techniques that involve interconnected smart sensors, volunteering and citizen science, and integrated process-based modeling are preferred when conducting comprehensive descriptions of the pond landscape, numerical assessments on their ecosystem services, and associated conservation cost analyses. Nature-based solutions are increasingly recognized as an important opportunity for coping with water-related crises. This paper presents the first synthetic perspective on the

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ecological roles of farm ponds in agriculturally dominated developing countries. The analytical framework and conservation suggestions are referential to sustainable rural development and the management of other small, scattered wetlands.

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1. Introduction

Farm ponds are small (1 m^2 to approximately 0.05 km^2), shallow (<8 m), natural or man-made surface depressions that permanently or temporarily hold water. They are frequently seen in agricultural regions in many countries (Yin and Shan, 2001; Céréghino et al., 2014; Grobicki et al., 2016). Owing to the low construction cost, high irrigation and drainage efficiency, and value for multiple uses, including drinking, fishing and washing, farm ponds have played an important role during development of human civilization (Miller, 2009; Mushet et al., 2014; Chen et al., 2018). In recent decades, however, the development of reservoir-based water systems has gradually weakened the importance of farm ponds in water supply. Many areas that were once farm ponds have been filled as a result of expanding urbanization (Huang et al., 2012; Hill et al., 2018) and agricultural intensification (Calhoun et al., 2014; Poschlod and Braun-Reichert, 2017) or have become isolated from one another due to the modification of ditches and streams (Fang et al., 2014). Thus, some obvious questions arise: Do farm ponds have functions beyond those of irrigation and water supply? Should they be conserved from contemporary degradation, and what are the challenges and solutions?

Conservation theory and practice pertaining to small, scattered wetlands (e.g., vernal pools, prairie potholes, farm ponds, gilgais, and cypress domes) was developed in the 1980s (Rashford et al., 2011; Raebel et al., 2012; Calhoun et al., 2014; Hunter et al., 2017). Several countries have implemented national conservation programs, including the Vernal Pool Association in the US, the Millennium Ecosystem Assessment in France, and the Pond Action in England, in conjunction with transnational research collaborations, such as the European Pond Conservation Network (Reid et al., 2005; Biggs et al., 2010; Lassaletta et al., 2010). Along with numerous scientific papers, which have tripled in number over the last decade (source: Thomson Reuters' Web of Knowledge^{SM}, October 2018), several reviews have highlighted farm ponds as regional biodiversity hotspots, providing habitat and refuges for some of the most endangered wetland plants, invertebrates and amphibians (Céréghino et al., 2014; Mushet et al., 2014; Hunter et al., 2017; Hill et al., 2018). Although developing countries require more effort to combat the increasing crisis of freshwater resource scarcity, most programs and findings have focused on developed countries (Liu and Yang, 2012; UN-Water, 2018). According to FAO (2013), shortage of freshwater resources in terms of both quantity and quality will occur in 1/5 of the developing countries by 2030 due to high agricultural water consumption and severe nonpoint source pollution. Moreover, the predominance of small farms makes the ponds more important to agricultural activities (e.g., paddy planting, fish farming, and unfenced poultry and livestock breeding) and rural life in peripheral areas (Mitsuo et al., 2014; Chen et al., 2018; Luo et al., 2018b). These circumstances point to a need for targeted and systematic analyses of farm ponds in the developing countries.

China is the largest developing country with a total population of 1.3 billion, with approximately 42% of the population living in rural areas. China has faced historical challenges in the conflict between irrigation water demand and spatiotemporally heterogeneous precipitation. To mitigate water shortages and regulate the distribution of water resources, farm ponds were first constructed in Anhui Province early in the 700s BCE, and then with the southward movement of agriculture during approximately the next thousand years, their prevalence extended from the middle and lower reaches of the Yangtze River to the Pearl River Delta and Yunnan Province (Yin and Shan, 2001; Zhang, 2009). After the foundation of the People's Republic of China (PRC) in 1949, farm ponds were vigorously developed and flourished as a unique natural-economic-social complex across southern China (Verhoeven et al., 2006; Liu et al., 2009; Yu et al., 2015). In recent decades, however, farm ponds, particularly small ponds, have faced a severe decline in numbers and malfunctions in terms of agricultural and ecological services. Although several nationwide environmental protection policies and legislations have been enacted to remedy water quality deterioration and water ecology degradation (e.g., the Water Pollution Prevention and Control Action Plan issued by the Ministry of Environmental Protection in 2015, the Revised Water Pollution Prevention and Control Law issued by the National People's Congress in 2017, and the River/Lake Chief Mechanism issued by the General Office of the State Council in 2016), protection of farm ponds in upstream areas has been entirely ignored. Across China, there has been a lack of systematic effort to characterize, monitor, and assess the waters' environmental and ecological status (Fang et al., 2014; Yu et al., 2015). The lack of such efforts is mirrored in other developing countries in Eastern Europe, South Asia, and South America, where farm ponds are used extensively for agriculture, but are excluded in conservation programs for wetland ecosystems (Poschlod and Braun-Reichert, 2017; Hill et al., 2018).

In view of the above scientific challenges and policy deficiencies, this study aims to analyze the ecosystem services, degradation threats, and conservation strategies associated with farm ponds in southern China. Although these water bodies exist in other regions across China, they are ubiquitous in southern China owing to the humid subtropical climate and prevalence of paddy planting. After a historical and spatial overview (Section 2), the importance of farm ponds over scales ranging from within-pond to regional is explored by reviewing historical documents and recent literature (Section 3). Current threats and management challenges for farm ponds are then investigated in the Chinese context (Section 4), followed by a proposed conservation framework derived from, but not limited to, recognized policies and techniques used to manage similar wetland ecosystems (Section 5). This study provides the first synthetic perspective to assist policy-makers and researchers in understanding and restoring the environmental and ecological values of farm ponds in developing countries.

2. Farm ponds in southern China

The history of farm ponds in China dates back to the Sinic civilization over 2600 years ago. Quebei, the earliest pond on record, was constructed during the Spring and Autumn Period (770 BCE to 476 BCE) under the leadership of Sun Shu-Ao, who was the Prime Minister of the Chu State (P.Y. Zhou et al., 2016). As described in *The Commentary on the Waterways Classic*, Quebei received water from three streams and had five outlets for irrigation and flood discharge. Large-scale water conservancies became prevalent during the Han Dynasty (206 BCE to 220 CE) as a result of the national policy of valuing agriculture above other industries. The total ponded area at that time was surprisingly large. For example, it was reported that the ponded area in Runan county, Henan Province, totaled 300 km^2, and its water storage capacity was far greater than that in the county in the 1970s (Hang, 2001). Owing to political infighting and warfare, the number of large ponds declined in both Tang and Song Dynasties (618 CE to 1279 CE). Even so, there was an increase in the number of small ponds, especially in the low mountainous and hilly areas of the Yangtze and Huai River

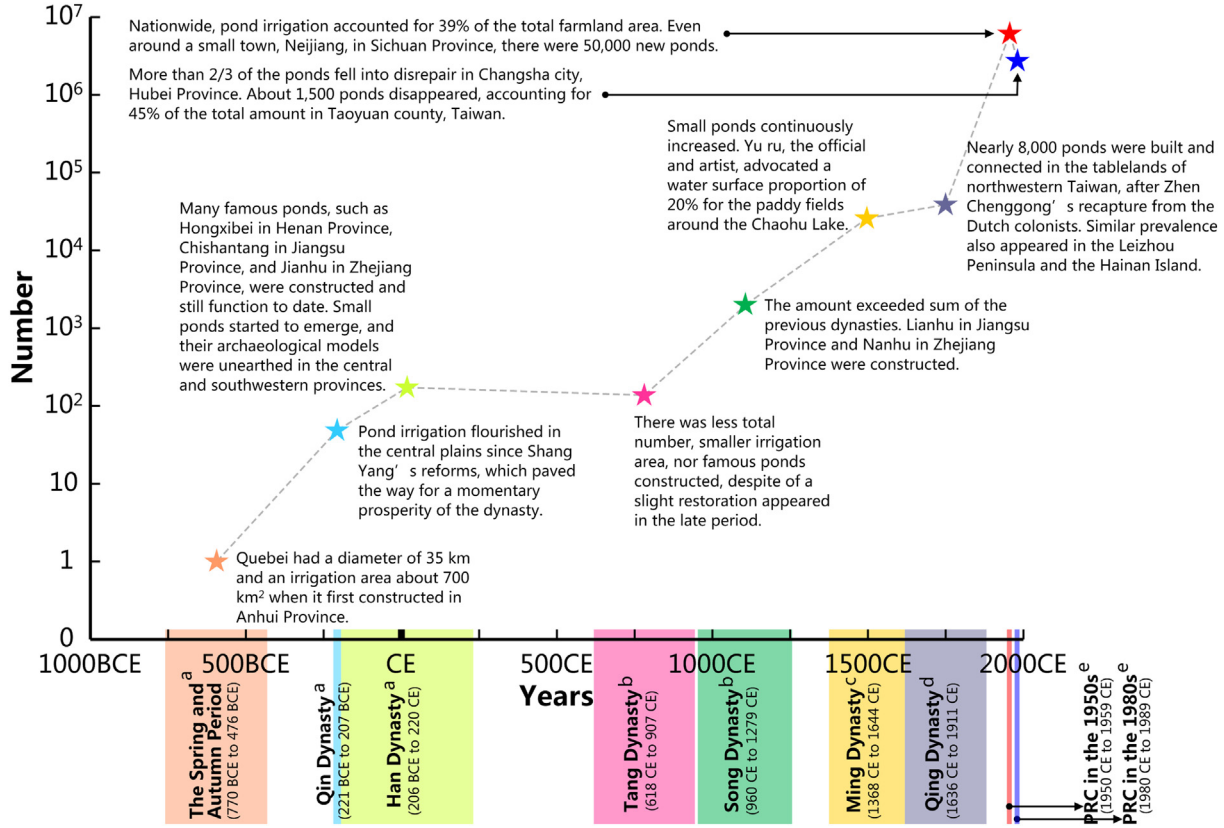

Number
Years
Nationwide, pond irrigation accounted for 39% of the total farmland area. Even around a small town, Neijiang, in Sichuan Province, there were 50,000 new ponds.
More than 2/3 of the ponds fell into disrepair in Changsha city, Hubei Province. About 1,500 ponds disappeared, accounting for 45% of the total amount in Taoyuan county, Taiwan.
Small ponds continuously increased. Yu ru, the official and artist, advocated a water surface proportion of 20% for the paddy fields around the Chaohu Lake.
Nearly 8,000 ponds were built and connected in the tablelands of northwestern Taiwan, after Zhen Chenggong's recapture from the Dutch colonists. Similar prevalence also appeared in the Leizhou Peninsula and the Hainan Island.
Many famous ponds, such as Hongxibei in Henan Province, Chishantang in Jiangsu Province, and Jianhu in Zhejiang Province, were constructed and still function to date. Small ponds started to emerge, and their archaeological models were unearthed in the central and southwestern provinces.
The amount exceeded sum of the previous dynasties. Lianhu in Jiangsu Province and Nanhu in Zhejiang Province were constructed.
Pond irrigation flourished in the central plains since Shang Yang's reforms, which paved the way for a momentary prosperity of the dynasty.
There was less total number, smaller irrigation area, nor famous ponds constructed, despite of a slight restoration appeared in the late period.
Quebei had a diameter of 35 km and an irrigation area about 700 km² when it first constructed in Anhui Province.
The Spring and Autumn Period (770 BCE to 476 BCE)
Qin Dynasty (221 BCE to 207 BCE)
Han Dynasty (206 BCE to 220 CE)
Tang Dynasty (618 CE to 907 CE)
Song Dynasty (960 CE to 1279 CE)
Ming Dynasty (1368 CE to 1644 CE)
Qing Dynasty (1636 CE to 1911 CE)
PRC in the 1950s (1950 CE to 1959 CE)
PRC in the 1980s (1980 CE to 1989 CE)

Fig. 1. Variations in the total number of farm ponds throughout Chinese history. A star indicates the amount estimated from references for a historical period highlighted in the same color. Additional comments are provided to explain some major features related to the farm ponds for each period. Citations: [a]Zhang (2009), [b]Li and Liu (1986), [c]Lü and Chen (2014), [d]Tan (2005), and [e]Hang (2001) and Yu et al. (2015).

basins. In the Qing Dynasty (1616 CE to 1911 CE), although pond irrigation was rarely recorded in historical files, small-scale water conservancies were widely implemented and voluntarily maintained by farmers (Lü and Chen, 2014). Along with rapid population growth and increasing food demand after the foundation of the PRC, small ponds flourished everywhere in southern China. However, their numbers and water storage capacity have declined sharply in recent decades due to flood damage, sludge blockage, and intentional filling or other destructive activities. As shown in Fig. 1, farm ponds played an indispensable role in China's traditional agriculture, and their number and function have been closely related to the policies of the central and local governments as well as the maintenance by farmers.

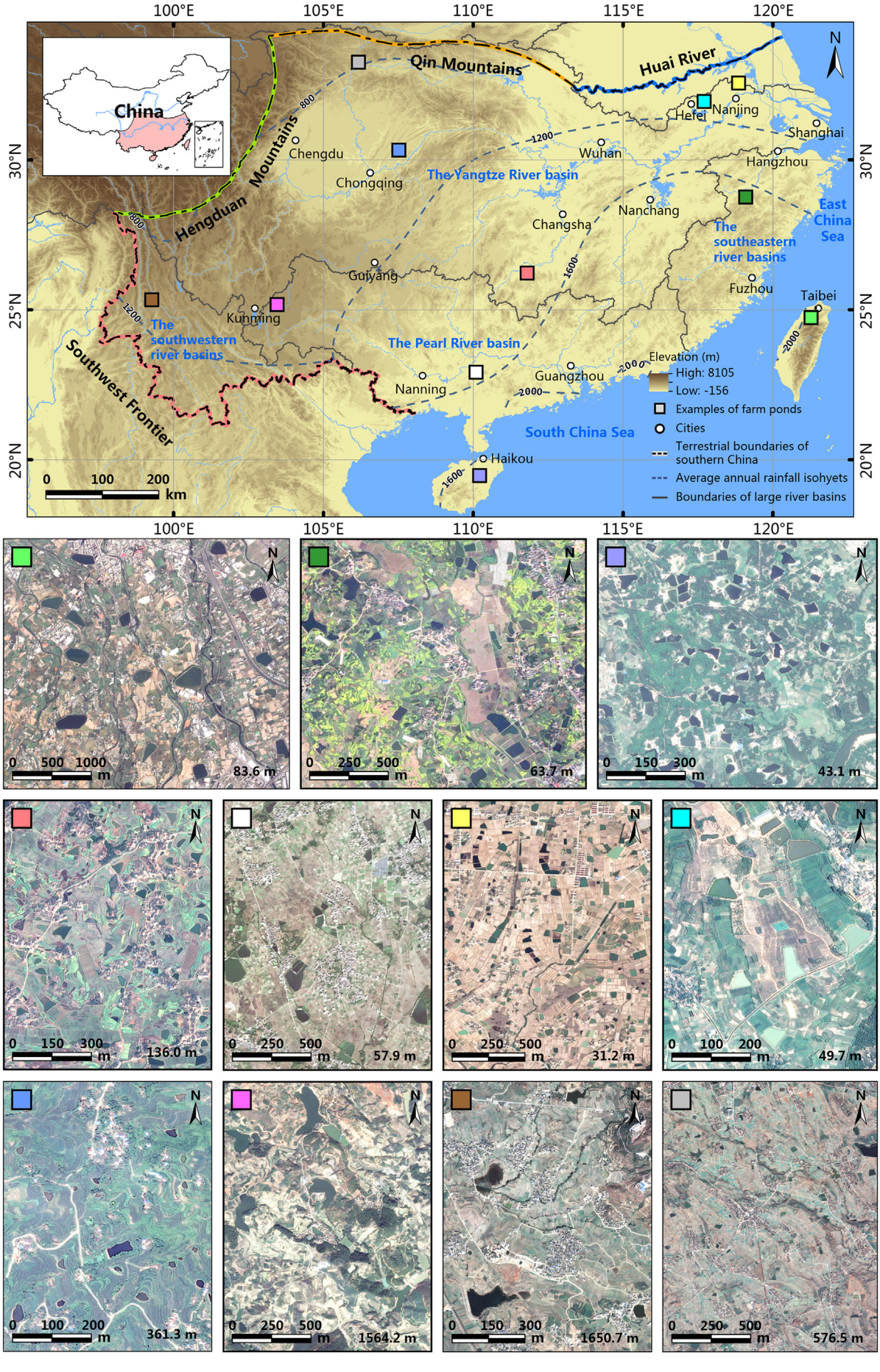
Farm ponds refer specifically to the abovementioned small-scale water conservancies to distinguish them from artificial lakes and reservoirs (Chou et al., 2013; Gao et al., 2016). Although farm ponds are rarely mapped at large scales (Tiner et al., 2015; Wu, 2018), the latest Google imagery (source: the 2018 DigitalGlobe, https://www.digitalglobe.com/) offers a feasible means to view their shapes and distributions in southern China. As demonstrated by the eleven examples presented in Fig. 2, farm ponds are distributed across (1) almost every province and municipality, (2) four rainfall isohyets with average annual rainfall of 800 mm, 1200 mm, 1600 mm, and 2000 mm, (3) landscapes with elevation ranging from 30 m to >1500 m, and (4) all four large river basins (the Yangtze River basin, the Pearl River basin, the southeastern river basins, and the southwestern river basins) and both island provinces (Taiwan and Hainan).

Farm ponds have a variety of common names in Chinese, such as 堰 (yàn in Mandarin, literally meaning weir), 坝 (accordingly, bà and dyke), 陂 (bēi and pond), 堨 (ài and blockage), 捺 (nà and restraint), 塘 (táng and pond), and 荡 (dàng and marsh). These names were derived from local customs and traditions, and they are also used to reflect various topographic features of the surrounding landscape (e.g., plains, valleys, and hills), hydrologic and vegetation conditions, and embankment structures of a farm pond (Yu et al., 2015). Despite these differences, advances in measuring systems have enabled the quantification of pond characteristics in various dimensions. Specifically, a single pond can be described by its shape, area, perimeter, depth, hydroperiod (i.e., annual water level variation and flood frequency), and other parameters (Tan, 2005). From a watershed or landscape perspective, groups of ponds can be described by their density (i.e., area proportion of water surface to farmland), connectivity (i.e., whether there is water transport between ponds via ditches or streams), fragmentation (i.e., a measure of dispersion and aggregation), contagion (i.e., a measure of spatial distribution), and other indicators (Huang et al., 2012; Fang et al., 2014).

3. Why are these small and scattered waters important?

Farm ponds in conjunction with the surrounding woods, farmlands, cottages, and water courses, constitute a unique pastoral landscape of small farms in southern China (Fig. 3). While storing rainwater, farm ponds can profoundly alter the hydrologic and nutrient cycling in the

Fig. 2. Boundaries of southern China and examples of farm ponds. From left to right and top to bottom, the images show (1) Taoyuan county, Taiwan, (2) Youbu town, Zhejiang Province, (3) Dingan county, Hainan Province, (4) Hongshan town, Hunan Province, (5) Luchuan county, Guangxi Province, (6) Chenji town, Jiangsu Province, (7) Huanglu town, Anhui Province, (8) Huwei town, Chongqin Municipality, (9) Luliang county, Yunnan Province, (10) Yongping county, Yunnan Province, and (11) Hangwang town, Shanxi Province. An average elevation of the area is provided on the bottom right corner of each image.


100°E
105°E
110°E
115°E
120°E
30°N
25°N
20°N
China
Qin Mountains
Huai River
Hengduan Mountains
Southwest Frontier
Chengdu
Chongqing
Wuhan
Hefei
Nanjing
Shanghai
Hangzhou
Nanchang
Changsha
Guiyang
Kunming
Fuzhou
Taibei
Nanning
Guangzhou
Haikou
The Yangtze River basin
The southeastern river basins
The southwestern river basins
The Pearl River basin
East China Sea
South China Sea
800
1200
1600
2000
Elevation (m)
High: 8105
Low: -156
Examples of farm ponds
Cities
Terrestrial boundaries of southern China
Average annual rainfall isohyets
Boundaries of large river basins
0 100 200 km
0 500 1000 m 83.6 m
0 250 500 m 63.7 m
0 150 300 m 43.1 m
0 150 300 m 136.0 m
0 250 500 m 57.9 m
0 250 500 m 31.2 m
0 100 200 m 49.7 m
0 100 200 m 361.3 m
0 250 500 m 1564.2 m
0 150 300 m 1650.7 m
0 250 500 m 576.5 m

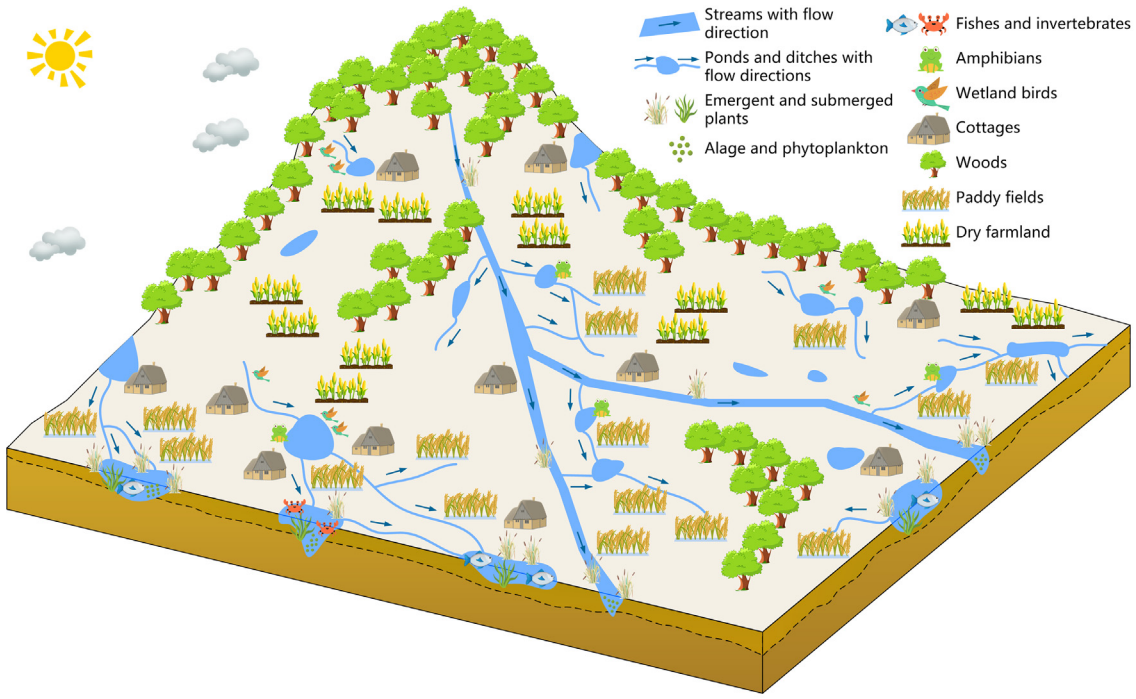


Fig. 3. A typical landscape with small, scattered farm ponds from low mountains to plains.

Table 1
Benefits of farm ponds in southern China.

Categories	Functions
Hydrological regulation	(1) Intercept surface runoff, (2) store water for irrigation and rural life, (3) reduce and postpone flood peaks, (4) recharge and discharge groundwater, and (5) increase humidity via water surface evaporation.
Pollution mitigation	(1) Reduce nutrients from agricultural drainage, (2) intercept sediment in surface runoff, and (3) sequester atmospheric carbon dioxide.
Biodiversity conservation	(1) Provide nutrient source for the food web, (2) wildlife habitat, and particularly, (3) spawning and incubation environment for endangered species.
Socioeconomic benefits	(1) Mitigate flood risk, (2) increase farmers' income, (3) constitute pleasant scenery and improve mental well-being, and (4) provide educational and recreational opportunities for the broader community.

watershed, and, as a consequence, lead to idiosyncratic riparian conditions to host flora and fauna. They also offer considerable social and cultural benefits, including improving physical and mental well-being and increasing awareness of environmental conservation at larger scales. The benefits of farm ponds are summarized in Table 1 and discussed in the sub-sections below.

3.1. Hydrological regulation and ecological cleanup

Farm ponds provide disproportionate contributions to hydrological and ecological functions that have lag, sink, and source effects on the physical, chemical, and biological status of downstream waters (Rains et al., 2016). Rainfall initially fills ponds and then runs off along the surface. This process helps to reduce flood peaks, contribute to groundwater recharge and discharge, and provides stream base flow for irrigation. In addition to the qualitative descriptions in ancient literature, such as in *The Odes of Chen*, *Classic of Poetry*, on-site monitoring and numerical assessment have quantified those hydrological functions. For example, in the Liuchahe watershed, Anhui Province, the 193 farm ponds that accounted for 6.2% of the total watershed area were observed to reduce irrigation water shortages from 333 to 138 mm in wet years and from 280 to 41 mm in dry years. During a heavy rainfall storm event (141 mm), the ponds reduced the flood peak from 2.5 to 0.3 m^3/s (Yin and Shan, 2001). Pond parameters, such as shape, area, and depth, determine their water retention in the catchment, while their spatial distribution is important to the water storage capacity and utilization of rainwater in the watershed (Verhoeven et al., 2006; Fang et al., 2014).

Farm ponds can reduce diffuse pollutants from agricultural drainage via many processes including interception and precipitation, plant uptake, microbial degradation, and sediment adsorption. Capps et al. (2014) discovered that oxygen transport through the stems of emergent and floating plants can create an aerobic environment at their root surface, where organic matter can be decomposed by aerobic microorganisms and ammonia can be nitrified by nitrifying bacteria. In the low-oxygen areas of the deep root zone, where anaerobic fermentation is prevalent, organic matter can be denitrified into carbon dioxide and methane. Moreover, farm ponds can remove the particle-bound phosphorus in runoff through sedimentation and enhance binding of soluble inorganic phosphate to Al^{3+} and Fe^{3+} in the sediments (Liu et al., 2009). A two-year monitoring in the irrigated area of Gaoyou county, Jiangsu Province, revealed that the concentration of total nitrogen and total phosphorus were reduced by 64.5 and 54.4%, respectively, by the groups of ponds and ditches (Peng et al., 2013). The reduction rate is determined by their connectivity, vegetation coverage and dredging operations (Mitsuo et al., 2014; Hansen et al., 2018; Chen et al., 2018).

3.2. Biodiversity conservation

As an essential component of the circular “crop-livestock-fish” production system, farm ponds increase biodiversity from within-pond to

regional scale. While crops are used to feed poultry and livestock, a large proportion of the manure produced by the poultry and livestock is applied into the ponds to promote fish growth, and the sediments in the ponds are returned to the land to improve soil fertility for crop production (Ongley et al., 2010; M. Chen et al., 2016). Although most of the manure is consumed by fish, it provides large amounts of nutrients for accelerating phytoplankton and zooplankton growth and supplies substrates for decomposing microorganisms. These increased biomasses, in turn, serve as food for a wide range of wildlife. In the ponds of the Liuchahe watershed, for example, Han and Sun (2007) reported a total of eight types of aquatic vegetation, including emergent plants, floating-leaved plants, and submerged plants. The vegetation covered approximately 12.6% of the pond surface area and formed different communities from the village, the farmland and the hillslope nearby. In the Taoyuan tableland, Huang et al. (2012) detected 94 bird species in pond areas. Serving as stepping stones between larger freshwater habitat, these ponds provide both a stopover site during winter migration for shorebirds and seabirds and attract many wetland birds to feed and nest. In addition, farm ponds are reported to provide habitat for many amphibians, such as frogs and toads, tortoises, and insects, including dragonflies, caddisflies, and midges. This even includes some species on the International Union for Conservation of Nature's Red List (https://www.iucnredlist.org/), which rely on the humid environment and abundant carbon resources in riparian areas, especially during the spawning and incubation periods (Raebel et al., 2012; Capps et al., 2014).

3.3. Socioeconomic benefits

A wealth of socioeconomic benefits stem from farm ponds. As enumerated above, the hydrological regulation and flood alleviation services contribute to social stability, and the improved nutrient cycling, particularly in the "crop-livestock-fish" system, is beneficial to agricultural production and farm economy. In a three-year study on abandoned ponds near Wuhan city, Hubei Province, for example, it was found that annual fish production amounted 2.2 to 2.6 kg/m^2. This generated a profit of $1.96 to $2.55 (13.5 to 17.6 RMB, $1 ≈ 6.90 RMB) per square meter (B. Zhou et al., 2016), and the whole city was estimated to benefit approximately $145 million (1 billion RMB) from the industry of pond aquaculture. Besides, *Phragmites* at the water's edge are reaped as raw material for papermaking in Hunan Province (Tian et al., 2011). Combined with farmlands, woods, and streams, farm ponds constitute a harmonious and nature-based rural residential scenery. For thousands of years, they have served as a traditional exchange place for neighbors' communicating and sharing life stories while washing, swimming and fishing. Such a water-centric lifestyle remains in the present, despite environmental and water quality deterioration due to nutrient enrichment from fertilizers and pesticides. In addition, these aquatic features may provide educational and recreational opportunities nationally and even globally. For example, Quebei has been honored as China's Key Relic Protection Unit since 1988 and a World's Heritage Irrigation Structure since 2015, attracting >100,000 domestic and foreign tourists annually (P.Y. Zhou et al., 2016). Although farm ponds triggered conflicts between different ethnic groups in northern Taiwan in the 1900s, a recent TV series called Beitang has aroused an appreciation of these land and water resources and introspection on their degradation in the Chinese community (https://www.imdb.com/title/tt7906402/).

4. What are the threats and management challenges?

The most overarching and pervasive threat to farm ponds is linked to their small size and wide distribution. Anthropogenic disturbances and natural processes are the cause of farm pond degradation, while management and conservation need to involve policy, numerical assessment, public awareness, and cost-efficiency analysis (Table 2).

4.1. Inadequate planning and regulations

The lack of rigor and consistency in planning small water conservancies is a widespread and chronic phenomenon (McGreavy et al., 2012; Poschlod and Braun-Reichert, 2017; UN-Water, 2018). Since ancient times, the construction and maintenance of farm ponds has been driven by the government prioritization of agriculture rather than assessment of the abovementioned ecosystem services. For example, in the golden age of the Han Dynasty, pond projects were launched nationwide, and >60% of the ponds were located in the agriculturally prosperous Yangtze and Huai River basins (Zhang, 2009). When it came to the subsequent Three Kingdoms Period, however, the ponds were damaged to restrict agriculture in neighboring realms, with Quebei losing 60% of its water surface area due to warfare (Hang, 2001). Today, China is facing grand challenges in feeding 22% of the world's population and land uses have been largely intensified to maintain the current average annual growth rate in agricultural production to be as high as 4.6%. As a result, many farm ponds have been converted to paddy fields, orchards, or threshing grounds (Yin and Shan, 2001). Moreover, centralized irrigation based on reservoirs and canals has weakened the role of farm ponds in water supply, resulting in further negligence and mismanagement of the ponds and increased vulnerability to floods and habitat losses (Liu and Yang, 2012).

Although recent evidence indicates that farm ponds contribute disproportionately more to aquatic biodiversity than larger and more widely studied freshwater systems, such as lakes and rivers, environmental legislation and management strategies of these features is far behind the needs due to the ignorance by the government. In Europe, the EU Water Framework Directive (WFD; 2000/60/EC) was implemented to protect and improve the quality of ground and surface waters, but, in practice, it only covers rivers and standing waters with a surface water area larger than 0.5 km^2, therefore excluding the vast

Table 2
Degradation threats and management challenges associated with farm ponds.

Categories	Threats and challenges
Inadequate planning and regulations	(1) In ancient China, a government emphasis on agriculture determined the increase and decline in the number of farm ponds, (2) currently, urbanization, land consolidation, and centralized irrigation contribute to their degradation, and (3) environmental regulations ignore these water bodies.
Rural nonpoint and mini-point source pollution	(1) Nonpoint source pollution can damage ecosystems, cause an imbalance in material and energy flow, and degrade ecosystem services, (2) mini-point source pollution from animal feeding operations and rural households is also significant, and (3) ponds are less capable of diluting pollutants.
Climate change	(1) Climate change can lead to increased air temperature, rising sea levels, and more frequent climatic extremes, and can also (2) cause abnormal hydroperiods and negatively affect invertebrate diversity and plant species composition.
Invasive species	(1) Invasive species, including plants, crayfish, and amphibians, (2) can be harmful to habitat structure and human health, and (3) may lead to secondary pollution if biological and chemical treatment are implemented.
Management	(1) Requires consideration of material, organisms and energy fluxes at various spatial scales, (2) need to involve awareness and understanding of the ecosystem services in the broader community, and (3) should be better quantified regarding the ecosystem services and conservation costs.

majority of temporary streams and wetlands (Lassaletta et al., 2010). Similarly, legislation in the US has protected the nation's navigable waters under the Clean Water Act since 1972, but these rules did not consider isolated and nonnavigable wetlands as a "significant nexus" within the hydrological system before two heated debates in 2001 and 2006 (Leibowitz et al., 2008). China has recently spent millions of dollars (billions of RMB) to remedy widespread environmental and ecological deterioration through various actions including converting farmlands to forests and grasslands, establishing wastewater treatment plants, and removing algae in lakes and rivers (Huang et al., 2019). Although these programs, in conjunction with management strategies, such as the River/Lake Chief Mechanism, and examination criteria, such as the Environmental Quality Standards for Surface Water (GB 3838-2002), have obtained phased achievements, the protection of farm ponds in upstream areas has been entirely ignored.

4.2. Rural nonpoint and mini-point source pollution

The extensive use of synthetic fertilizers and manure is a major characteristic of modern agriculture, and the associated discharge of nitrogen and phosphorus has become a major source of nonpoint pollution in rural areas. These pollutants can damage ecosystems, impair material and energy flows, and reduce or eliminate ecosystem services. For example, ammonia can increase pH and temperature of ponded waters and can be toxic to fish and invertebrates (Zheng et al., 2017). At elevated concentrations, nitrogen and phosphorus are the main causes of algal blooms in surface water, while nitrate in drinking water sources are linked to birth defects, methemoglobinemia in infants, and high blood pressure in adults (Ongley et al., 2010; M. Chen et al., 2016). In addition, it is noteworthy that farm ponds are more vulnerable to pollution than larger water bodies, due to their smaller capacity of diluting pollutants physically, chemically, or biologically, especially when the surrounding drainage network is modified (Huang et al., 2012; Céréghino et al., 2014).

Although intensive point source discharge, such as industrial wastewater, is rare in agricultural regions, mini-point pollution sources, including animal feeding operations and domestic sewage and wastes, pose nonnegligible threats to the ecosystems of farm ponds. According to the First National Census of Pollution Sources (Ministry of Agriculture of the PRC, 2009), poultry and livestock feeding produces 12.7 Tg (1 Tg = 10^{12} g) total nitrogen and 0.2 Tg total phosphorus annually, of which approximately 43.6% originates from unfenced feeding operations. Scattered domestic animals live in riparian areas, discharging their manure and urine into the water. Domestic sewage in these areas is barely treated before being discharged into ponds and ditches owing to the lack of sewage collection and treatment facilities (Ongley et al., 2010). In addition, domestic wastes, including plastic bags, obsolete electrical appliances, and food residues are usually discarded into the water, resulting in persistent microplastic and heavy metal pollution as well as unpleasant color and smell (Zhang et al., 2018).

4.3. Climate change

Farm ponds, owing to their small catchment area and size, are vulnerable to changes in temperature and precipitation patterns. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the increase in temperature was highest during the past century, while extreme precipitation and storm events have increased dramatically, and sea levels have risen 0.17 to 0.21 m in the Northern Hemisphere (Stocker, 2014). In addition, owing to the combined effects of El Niño and La Niña events, East Asia, especially the coastal provinces of southeastern China, usually suffers continuous precipitation and floods from early spring through the entire monsoon period (i.e., March to July, Karori et al., 2013; Luo et al., 2018a). These climatic extremes can cause an abnormal hydroperiod and negatively affect invertebrate diversity and plant species composition. For example, widespread droughts occurred almost every year in the southwestern regions during the past two decades, and many ponds dried up and were abandoned (Han et al., 2014). In the southeastern regions, however, soil erosion tends to be severe in the low mountains and hills, where frequent dredging operations are required to avoid siltation, eutrophication, and flooding.

4.4. Invasive species

Invasive species can pose a serious threat to freshwater biodiversity. China's humid weather conditions, widespread transportation network, and fragmented habitat of native species have provided favorable conditions for exotic and invasive species. Invasive species in farm ponds include plants, crayfishes, and amphibians (Yan et al., 2001; Wang et al., 2017). For example, the growth and propagation of water hyacinth can cover the entire water surface, blocking light, suppressing the growth of plankton, and causing severe degradation of other aquatic flora and fauna. These plants can even be harmful to human health, promoting the breeding of rats, flies, and other carriers of bacteria, if the waters simultaneously contain domestic wastes. To reduce such adverse effects, the Shanghai government has spent $2.18 million (15 million RMB) annually to remove water hyacinth in the suburbs, but some biological and chemical agents have resulted in secondary pollution (Lu et al., 2007).

The above natural and anthropogenic threats can be significant by their own, but the interactions of the changing climate, invasive species, and landscape degradation due to increasing demands for food, space, and water resources make the need for suitable management strategies clear if we are to sustain the multifarious benefits of these aquatic features.

4.5. Management challenges

Farm ponds act as biological, physicochemical, and ecological hotspots within an agricultural matrix and require management at both the within-pond and landscape scales (Chou et al., 2013; Mushet et al., 2014; Hill et al., 2018). Because the hydroperiod of farm ponds is mainly determined by the local climate, microtopography, and water consumption, they are extremely susceptible to changes in the surrounding land uses and crop types. Due to their small water area and volume, farm ponds are also very sensitive to alterations in chemistry of sediments and pollutants. In addition, farm ponds usually support life forms of amphibians from larva to adult and migratory birds from hundreds of miles away, making the adjacent terrestrial habitat an integral part of their ecosystem services. Direct losses or degeneration of these water bodies decreases the regional wetland density and increases travel distances for wildlife, particularly those relying on multiple aquatic resources. In the past, studies on farm ponds have been focused on their single ecosystem service (Chou et al., 2013; Gao et al., 2016). Integrated pond management is usually difficult to achieve due to predefined priorities, funding limitations, and narrow research objectives that lack the scientific understanding of those multiscale processes (Spiteri and Nepalz, 2006; Raebel et al., 2012). Therefore, one major challenge is to manage, conserve, and restore ponds by integrating several spatial scales, and taking into account all fluxes of materials, organisms, and energy. Although it is very difficult, being aware of the implications of pond management across these aspects is important.

Limited public awareness and understanding of small, scattered wetlands complicates the management of farm ponds. Compared with agricultural irrigation and flood alleviation, the less visible ecosystem services (e.g., providing habitat for endangered species and contributing to groundwater recharge and discharge) are not widely recognized, which diminishes local support for public conservation actions (Hunter, 2005; Zhang, 2009; Golden et al., 2014). On the other hand, some distinguished natural landscapes usually have a flagship wildlife

species to capture the hearts and minds of the public, such as pandas for the Chinese bamboo forests and penguins for the Antarctic ice sheets. Although migratory birds or amphibians may be good candidates if marketed well, farm ponds lack such charismatic species but can be regarded as breeding havens for some unpleasing animals, such as poisonous snakes, mosquitoes and leeches. Another challenge is therefore to improve the broader communities' understanding of the ecosystem services even though farm ponds seem only related to the rural households nearby.

The small size, large number, and wide distribution of farm ponds make developing conservation strategies confusing and costly. Ecosystem services of farm ponds must be better articulated to change the perceptions of the public and authorities. Some naturalist associations and scientific organizations, such as the European Pond Conservation Network (https://freshwaterhabitats.org.uk/), the Million Ponds Project in the UK (https://www.arc-trust.org/), and the Taoyuan Pond and Waterway Conservation (https://conservation.forest.gov.tw/), are active in compiling documents, illustrations, and recommendations, but few provide numerical assessments to assist practical conservation actions. Widespread benefits and concentrated costs can challenge conservation strategies based on negotiations with individual landowners who have ponds on their property but envision a more profitable use of the land (Shogren et al., 2003). This problem is more difficult in China, as small water conservancies are formally state owned, but paradoxically, the dredging and reinforcement of farm ponds are generally funded by local communities (Tan, 2005). While the ecological and social importance of farm ponds can be quite significant, only limited value is offered to small farmers who have ponds in their fields, which decreases their interest in conserving the projects. Therefore, management policies and approaches that quantify ecosystem services and recognize the full extent of conservation costs are more likely to succeed in navigating these challenges.

5. Policies and approaches for farm pond conservation

If farm ponds are conceptualized as complex ecosystems, their role in wetland conservation planning is quite evident. In this section, we address three conservation policies, including public awareness building, top-down regulations and bottom-up engagement, and sustainable management and utilization, as well as three technical approaches, including inventory mapping, IoT-based collaborative monitoring, and numerical assessment, from similar practices in, but not limited to, wetland protection. These methods are oriented to the small, scattered characteristics of farm ponds, and involve various stakeholders, including community members and government sectors, to ensure a long-term, collaborative conservation framework in developing countries. Fig. 4 shows how these methods, stakeholders and pond landscape may fit together logically, and each of the methods is discussed in the sub-sections below.

5.1. Public awareness building

The critical first step of public awareness building is to ensure that the terms “small wetlands”, “freshwater ecosystems” and “landscape degradation” are in the lexicon of farmers, local officials, rural planners, and urban visitors. Education serves as a formal and fundamental method to build such environmental awareness and to make conservation knowledge explicit and widespread (Varela-Losada et al., 2016). In addition to classroom education programs, on-site environmental activities can enhance student learning and instill an intrinsic valuation of nature. For example, survey data indicated that primary school students exhibited increased interest in soil and water sciences and willingness to protect red-crowned cranes after four seasonal visits to the Zhalong Nature Reserve, northeastern China (Zhao, 2006). Environmental-friendly attitudes and behaviors have also been demonstrated to be transferable from children to their families (Damerell et al., 2013), which is important because animal feeding operations and household water management are closely related to the ecosystems of farm ponds.

Informal education by means of newspapers, radio, television, and the internet, is more flexible and diverse, translating scientific findings into policy and converting environmental knowledge into action for various stakeholders (Greenhow and Lewin, 2016). For example, the Vernal Pool Association has operated a promotional website (https://www.vernalpool.org/) since 2005 and identified >300 vernal pools in conjunction with their invertebrates' lifecycles in Massachusetts, US, where the filling and draining of ephemeral ponded wetlands is prohibited. Similarly, in the intertidal zones of Zhejiang Province, 8000 popular science readings and 1000 wildlife photo albums were

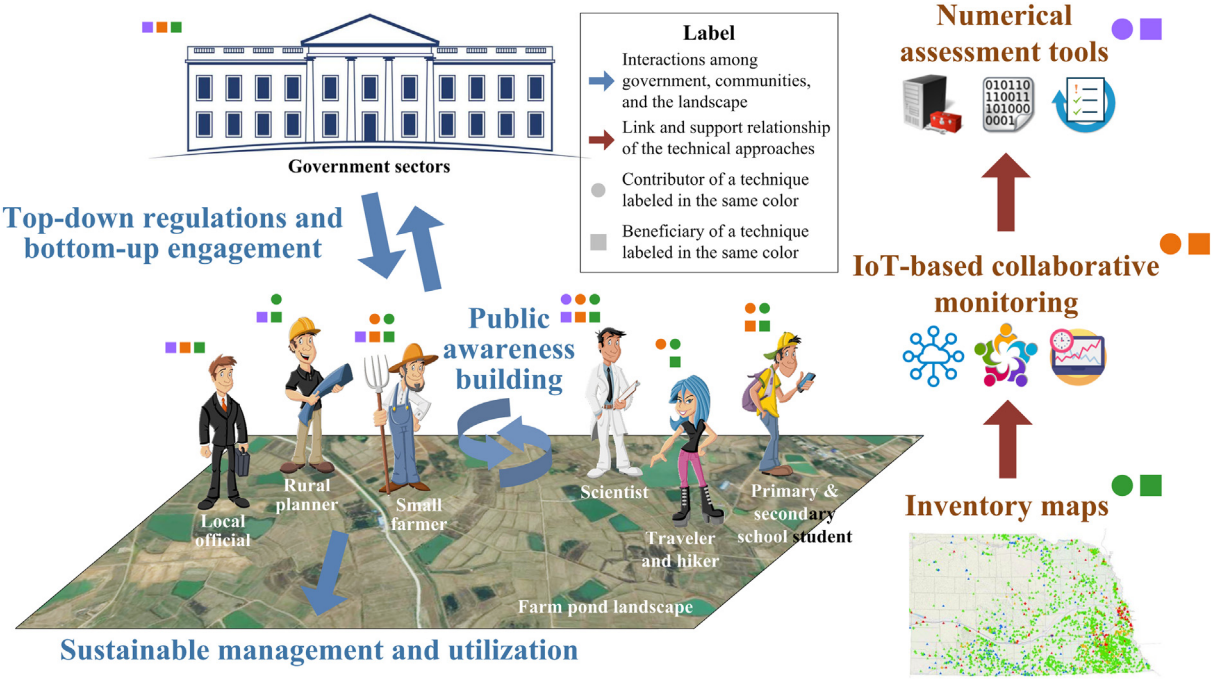


Fig. 4. A technopolitical framework for conserving farm ponds.

compiled and disseminated to rural residents during World Wetlands Day and Bird Loving Week from 2011 to 2014. These substantial investments in public education have helped to implement a strong regulatory basis for the restoration of mangrove swamp and estuarine wetland (Tang, 2015).

5.2. Top-down regulations and bottom-up engagement

Regulations promoting the conservation and management of small, scattered wetlands may range from restrictive local protections at the pond scale and across hundreds of meters of adjacent habitat at the landscape scale to broader national guidelines and international commitments (Biggs et al., 2010; Fang et al., 2014; Mitsuo et al., 2014). At any governmental level, top-down regulations have the advantage of setting clear rules but usually lack local understanding and enforcement jurisdiction of the various stakeholders being regulated. This is particularly true for farm ponds, which are sometimes closely related to agricultural activities and rural life. Hence, their management may best be achieved by combining top-down approaches, which set an overall standard, and bottom-up engagement, which ensures effective complements via more tailored and voluntary actions. For example, vernal pool conservation regulations at the federal and state levels only include formal definitions, criteria to support pool prioritization, and a basis for delimiting buffer zones, while local programs are more concerned with the economic benefits of land use and the surrounding flora and fauna in Maine, US (Calhoun et al., 2014).

Top-down regulations have gradually shifted from rivers and lakes to small, manmade, or natural shallow waters in developed countries, as the latter are numerous, typically outnumbering the larger waters, and can be regarded as biogeochemical hotspots in virtually all terrestrial environments (Leibowitz et al., 2018). For example, the US Environmental Protection Agency concluded that ponded wetlands are effective in riverine nitrate removal and thus are “waters of the US” under the Clean Water Act (Leibowitz et al., 2008). The EU Water Framework Directive has recently recognized the importance of intermittent headwater streams due to their vulnerability to anthropogenic pressures and significant influence on downstream water quality (Lassaletta et al., 2010). However, such “legal” standing for farm ponds is lacking in China's environmental legislation. Following the institutional reform of the State Council in 2018, the Ministry of Ecology and Environment, together with the Ministry of Natural Resources, Ministry of Water Resources, and Ministry of Agriculture and Rural Affairs, recommended standardization of construction, operation, and maintenance of farm ponds, especially those in disrepair or in areas vulnerable to floods and landslides. These ministries would also be responsible for the proposal of relevant laws and regulations, such as “Procedures to Build a Farm Pond”, “Plans for Farm Pond Protection”, and “Farm Pond Restoration Provisions”.

Meanwhile, bottom-up initiatives must be encouraged. On-site pond conservation programs usually require understanding of natural conditions (e.g., hydrology, soil, and geology) and agricultural practices in peripheral areas. The involvement of local communities can provide such information and also help to enhance the effectiveness and continuous improvement of those programs (Calhoun et al., 2014). Citizen science has become a popular way to engage “nonprofessionals” in ecological assessment and environmental protection across scattered areas (Zheng et al., 2017). With regard to farm ponds, recruiting voluntary or somewhat incentive-based farmer scientists and holding regular workshops for their family members is recommended to foster a sense of responsibility, mutual surveillance, and eventually collaborative conservation, as has been tested in farmer-participatory rural reform in the Chenzhuang village, Jiangsu Province (Yang and Chen, 2017; Chen et al., 2018).

Like participant incentives, conserving natural resources is also sometimes expensive and time-consuming owing to the need for infrastructure, maintenance, informational material, etc. Therefore, it is essential to develop partnerships with different communities and identify opportunities to meet disparate goals with desirable outcomes for various stakeholders (Spiteri and Nepalz, 2006; McGreavy et al., 2012). In southern Saskatchewan, Canada, for example, prairie pothole protection is combined with govern funding and investments from nongovernmental organizations (Rashford et al., 2011). To introduce up-to-date technologies and management skills in urban stormwater management, Chinese authorities have adopted the participation of private and foreign investors since the late 1990s. Their cooperation has started a unique form of Public-Private Partnership (PPP) projects, which take advantage of top-down regulation from government sectors and the flexible operation of market-oriented entities (Lee, 2010). Despite potential operational risks, including postponed approvals and imperfect supervision, these diversified opportunities are referential to farm pond conservation, especially when funds and techniques are limited.

5.3. Sustainable management and utilization

Small, scattered wetlands are arguably best managed using the mesofilter strategy (Hunter, 2005; Hunter et al., 2017), where features that may be integrated ecosystems in their own right, or ecological elements within a larger context can, by nature of their small size, move towards sustainable management. As a unique natural-economic-social complex, farm ponds also require appropriate management to collect stormwater, mitigate flood risk, and provide considerable economic and cultural benefits in rural areas (Yin and Shan, 2001; Mitsuo et al., 2014; Yu et al., 2015). In view of their importance to both nature and humanity, such management needs to incorporate approaches that range from within-pond practices specific to water and sediments to landscape-scale strategies that recognize their functions as wetland complexes that are embedded within, and may be integral to, larger ecosystems.

From historical documents on paddy planting to recent water conservancy practices, farm pond management, including dam design and construction and pond repair and dredging, have always been highlighted in southern China. For example, early in the Spring and Autumn Period, *The Records of Examination of Craftsman* proposed that a dam's cross-section should be trapezoidal in shape and the slope of the trapezoid edge is recommended to be 1:1.5 to 1:2.0 for structural stability. With regard to regional pond planning, *The Huainanzi Shuolin Discourse* compiled in the Han Dynasty stated that waters with a total area of 0.1 km^2 and an average depth of 2 m can mitigate droughts in surrounding farmland of 0.4 km^2, indicating that a pond density of 25% is appropriate for agricultural irrigation. Pond repair and dredging were biyearly carried out after crop harvest between the Yangtze and Huai River (Lü and Chen, 2014). Despite increasing flood risk and soil erosion due to climate change and a dwindling number of small farmers in the countryside, these management traditions are indispensable to maintain water capacity, improve water quality, and promote nutrient cycling.

Protecting farm ponds from degradation and destruction is a multiscale issue that requires broader perspectives and strategies. For example, conservation prompts, such as “Don't litter” signs, have proven useful to reduce floating wastes from rural households and tourists, as they are highly specific, proximal to a site, and can be stated in a friendly manner to motivate one's responsibility (Osbaldiston and Schott, 2012). In addition, following the experience of water caltrop planting in Anhui Province and *Phragmites* growing in Hunan Province (Liu et al., 2009; Tian et al., 2011), special attention needs to be paid to aquatic vegetation, as it provides habitat to amphibians and benthic invertebrates and is easily consumed by the farmed fishes. In addition, low-impact development, including the use of pervious pavement and the construction of rain gardens and forested buffers in riparian areas, is encouraged in rural areas, as it has been included in urban planning. When constructed at an optimized density and connectivity, farm ponds can act as nature-based “sponges” (Yu et al., 2015; UN-Water,

2018), reducing nutrient loads into downstream waters (Hansen et al., 2018; Leibowitz et al., 2018).

5.4. Inventory mapping

To effectively manage and conserve farm ponds individually and at a landscape scale, it is essential to have a spatially explicit inventory combined with a collection of the hydrological and ecological status of the ponds, including information on the adjacent agricultural matrix. Remote sensing methods have been widely used to analyze pond dynamics, e.g., the loss rate and driving forces in the Taoyuan tableland (Fang et al., 2014), but farm ponds are rarely mapped at large scales, as they are usually disregarded or not documented in places where wetland inventories are compiled and are difficult to automatically update from high-resolution, nationwide imagery (Tiner et al., 2015; Wu, 2018). In addition, the ability to identify farm ponds varies greatly depending on the natural conditions, such as water level fluctuations and adjacent vegetation coverage. For example, in evergreen and mixed forest landscapes in the northeastern US, only 43% of the confirmed temporary pools were detected by aerial photography. Even in open areas, remote detection can be limited by atmospheric conditions and the spatial resolution of the sensors being used (DiBello et al., 2016). However, technological advances are constantly improving this work. The availability of high-resolution light detection and ranging (LiDAR), synthetic aperture radar (SAR), hyperspectral, and multispectral data has increased the feasibility of detecting water bodies as small as 1×1 m. Moreover, the introduction of multisensory and multiscale data fusion techniques has enabled the large-scale mapping of small wetlands with unprecedented accuracy (Tiner et al., 2015).

Despite the abovementioned management constraints and technological challenges, inventory maps of ponded waters can be developed at multiple scales from field surveys, image interpretation, and voluntary programs using farmer scientists to identify their location, extent, and ecosystem structure (Calhoun et al., 2014), to conduct large-scale inventories associated with hydrological and ecological assessments to better support research, management, and government initiatives, as has been done in other specialized databases with numerous, scattered points of interest (W. Chen et al., 2016).

5.5. IoT-based collaborative monitoring

Recent developments in environmental monitoring has enabled quantitative descriptions of the physical, chemical, and biological characteristics of water bodies over time and space. In this process, one of the most important features is the Internet of Things (IoT), which provides a network of various smart devices that sense, interpret, and react to the environment (Perumal et al., 2015). Owing to their low cost, ease of access, and tailored devices, IoT-based techniques have inspired engineers and private entities to either build their own sensors or modify off-the-shelf equipment to realize the integrated and real-time detection of hydrological, water quality, aquatic biota and soil conditions. For example, in Hubei, Jiangsu, Guangdong, and other provinces, connected sensors coupled with imbedded knowledge base have facilitated aquatic plant growth, nutrient management, and disease prevention in shrimp breeding ponds, transforming traditional inland fisheries and aquaculture into data-driven and intelligent activities (Ma et al., 2012).

Collaborative efforts from different communities can expand the horizons of environmental monitoring and complement infrastructure and fixed observation stations. For example, mobile phones with GPS, photography, and social media applications have proven effective in collecting data on the color and transparency of surface waters by citizens, as has been implemented in the River Chief Mechanism (Zheng et al., 2017). Simple and inexpensive water test kits, available from many pet stores or online retailers, are useful to small farmers when preventing water quality degradation in fish ponds (Naigaga et al., 2017). High-throughput sequencing of DNA extracted from water samples serves as a quick, cost-effective and standardized method for scientists and conservation agencies when evaluating rare and threatened species across a wide range of taxonomic groups (Thomsen et al., 2012). By properly integrating these discrete results with consecutive data, IoT-based monitoring can be extended to a human-centered network with wide community involvement. Fig. 5 shows an integrated monitoring system being developed for farm pond conservation in the Chenzhuang village. Although this is a long-term effort, the GIS-based data framework will provide a solid basis for understanding pond ecosystem services.

5.6. Numerical assessment tools

To balance the costs and benefits of farm pond conservation, the hydrological, biogeochemical, and biodiversity functions that support ecosystem services and socioeconomic value should be assessed in a standalone or comprehensive manner (Fang et al., 2014; Hill et al., 2018). For example, based on streamflow observations, Gao et al. (2016) discovered a decreasing trend of water retention from downstream to upstream in the pond landscape of Chenji town. Chou et al. (2013) employed questionnaires, the fuzzy Delphi method, and an analytic hierarchy to assess the habitat suitability of pond-breeding amphibians in Yunlin county, Taiwan. Taking aquatic environments, terrestrial settings, and landscape connectivity into account, their results revealed that 19% of the 481 farm ponds were rich in frog species with high conservation value. In contrast to these single-criteria analyses, the vernal pool assessment in the northeastern US relies on both indoor and outdoor citizen-training sessions, as the former requires aerial photointerpretation and GIS to delineate waters, and the latter includes field surveys of egg masses, amphibians, and invertebrates (McGreavy et al., 2012; DiBello et al., 2016). Applied in a larger context, this method can provide a detailed assessment of aquatic features but requires labor-intensive efforts to establish a sound monitoring database beforehand.

Process-based models, which are based on a theoretical understanding of ecological processes and a set of computer programs, are useful to assess wetland dynamics and associated conservation decisions, especially when the required data are discrete and deficient (Ongley et al., 2010). Popular model categories include (1) watershed models, such as SWAT, HSPF and AnnAGNPS, that describe rainfall-runoff processes and often include an associated biogeochemical module that routes point and nonpoint source pollutants from the landscape to the stream, (2) hydrodynamic and water quality models, such as WASP, FEWMS and EFDC, that emphasize flow circulation, pollutant fate and transport and the interactions among the sediment, nutrients, phytoplankton and macrophytes in surface waters, (3) groundwater models, such as MODFLOW and HydroGeoSphere, that estimate the movement of subsurface flows through saturated porous media, and (4) ecosystem models, such as AquaSim, Ecopath with Ecosim and AEMON, that quantify the ecological relationships and evaluate the costs and benefits of wildlife conservation (Golden et al., 2014; Janssen et al., 2015; Rains et al., 2016). Although these models are deliberate in their respective domains, detailed modeling of pond dynamics is more complex, as it simultaneously includes surface and subsurface hydrological processes, biogeochemical cycles in ponds and ditches, and ecological processes at various spatial scales (Rains et al., 2016; Chen et al., 2018). Therefore, appropriate integration of these models is expected to assess the ecosystem services of farm ponds individually and comprehensively.

To make the modeling tools more immersive and comprehensible, several emerging techniques can be employed, such as serious games and gamification and augmented and virtual reality, which have been tested in land management (Schulze et al., 2015), water resource protection for over-pumped aquifers (https://savethewater-game.com/), and climate change adaption involving sociopolitical events, energy consumption, population growth, etc. (http://www.soothsayergames.com/). These technical advances are helpful to illustrate

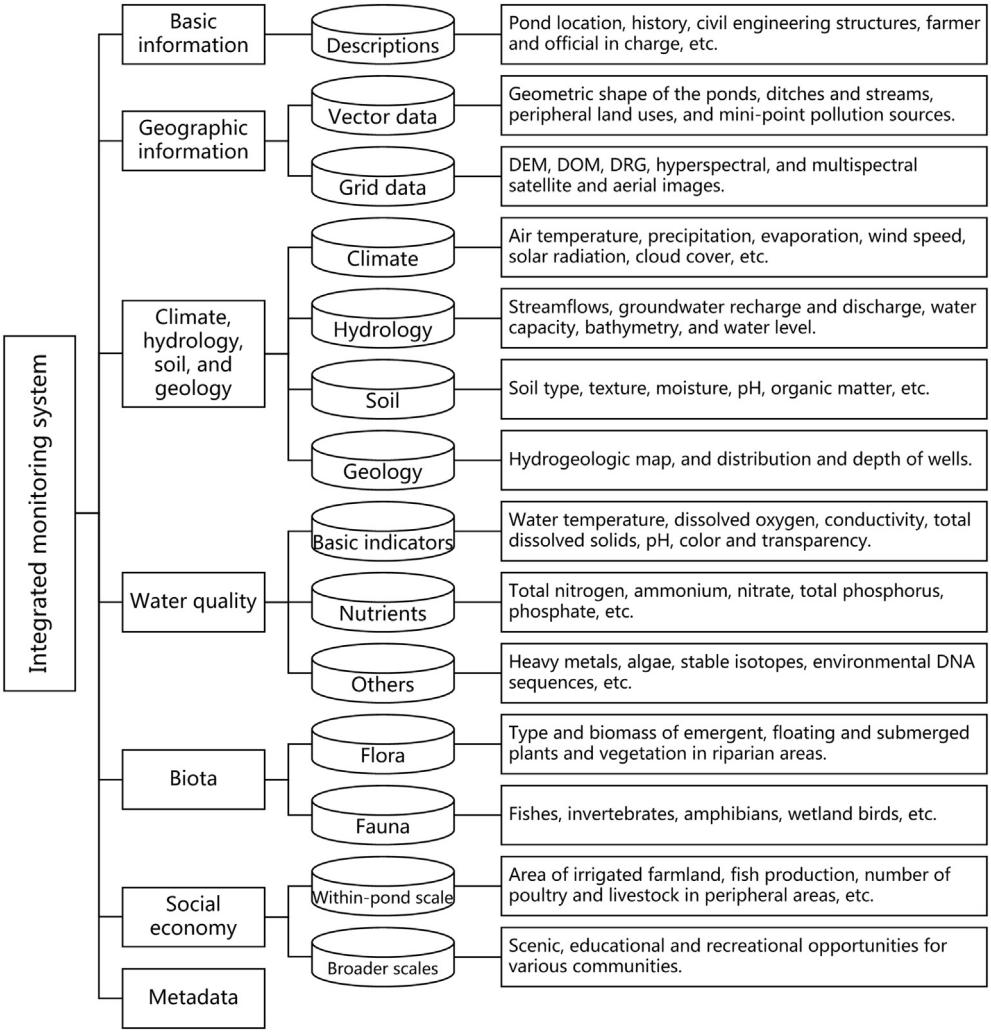

Integrated monitoring system
Basic information
Descriptions
Pond location, history, civil engineering structures, farmer and official in charge, etc.
Geographic information
Vector data
Geometric shape of the ponds, ditches and streams, peripheral land uses, and mini-point pollution sources.
Grid data
DEM, DOM, DRG, hyperspectral, and multispectral satellite and aerial images.
Climate, hydrology, soil, and geology
Climate
Air temperature, precipitation, evaporation, wind speed, solar radiation, cloud cover, etc.
Hydrology
Streamflows, groundwater recharge and discharge, water capacity, bathymetry, and water level.
Soil
Soil type, texture, moisture, pH, organic matter, etc.
Geology
Hydrogeologic map, and distribution and depth of wells.
Water quality
Basic indicators
Water temperature, dissolved oxygen, conductivity, total dissolved solids, pH, color and transparency.
Nutrients
Total nitrogen, ammonium, nitrate, total phosphorus, phosphate, etc.
Others
Heavy metals, algae, stable isotopes, environmental DNA sequences, etc.
Biota
Flora
Type and biomass of emergent, floating and submerged plants and vegetation in riparian areas.
Fauna
Fishes, invertebrates, amphibians, wetland birds, etc.
Social economy
Within-pond scale
Area of irrigated farmland, fish production, number of poultry and livestock in peripheral areas, etc.
Broader scales
Scenic, educational and recreational opportunities for various communities.
Metadata

Fig. 5. The data framework of an integrated monitoring system for farm pond conservation.

interdisciplinary teaching and education regarding pond conservation and the complex interrelations between the ponds and human well-being.

6. Conclusions

Nature-based solutions are becoming increasingly recognized as important for addressing the complex challenges in hydrology, ecology, and biodiversity. The multiple functions of small, scattered wetlands that support ecosystem services and their socioeconomic benefits in different countries make these water bodies interesting to scientists and decision-makers. As unique pastoral landscapes in rural areas, farm ponds have represented such aquatic features throughout history in southern China but have not received the attention they deserve, especially in terms of government regulation and environmental policies. Urbanization in conjunction with land consolidation and the prevailing reservoir-based irrigation systems have now engendered the degradation of these small wetlands, while rural nonpoint and mini-point source pollution, increasing climatic extremes, and invasive species have expedited water quality deterioration and adjacent ecosystem degradation.

A wide array of conservation strategies is proposed, starting with public awareness building and inventory mapping, thus creating a foundation for appropriate conservation. Top-down regulations and bottom-up engagement are simultaneously encouraged to ensure policy effectiveness and public initiatives, while sustainable management and utilization are necessary to reduce adverse influences on the aquatic ecosystems. Ultimately, with wide participation, IoT-based collaborative monitoring and the integration of process-based models are recommended to quantify the ecological processes, ecosystem services, and cost-efficiency of conservation programs. As a first synthetic perspective to emphasize the ecological roles of farm ponds in agriculturally dominated developing countries, this paper calls attention to these endangered water bodies and encourages sustainable rural development among policy-makers, stakeholders, and the general public. The analytical framework and comprehensive suggestions are also referential to other small, scattered wetlands for which restoration efforts are required.

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